Natural regeneration characteristics of *Pinus sylvestris* var. *mongolica* forests on sandy land in Honghuaerji, China

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Abstract: Natural regeneration in Mongolian pine, *Pinus sylvestris* var. *mongolica*, forest at Honghuaerji of China (the original of the natural Mongolian pine, forest on sandy land) was studied in 2004. The total mean values of regeneration indexes were higher in mature stands (more than 80% individual stems were older than 50 years), the maximum of regeneration index reached 29 seedlings · m^{-2}, with lowest values in the younger stand, e.g., in 32-year old and 43-year old stands. The stand age was an important factor determining the natural regeneration, which was the best in the older stands in this investigation (e.g. about 80-year old). The regeneration index seemed not to be closely in relation to canopy openness although Mongolian pine is a photophilic tree species. In each type of gaps, natural regeneration was very well. Regeneration indexes were satisfactory at the south and east edges in the circle gaps; and at the east edge of the narrow-square gaps. Results indicated that Mongolian pine, seedlings could endure shading understory, but it would not enter the canopy layer without gap or large disturbance, e.g., fire, wind/snow damage or clear cutting etc. These results may provide potentially references to the management and afforestation of Mongolian pine, plantations on sandy land in arid and semi-arid areas. Researches such as the comprehensive comparisons on regeneration, structure and ecological conditions and so on between natural Mongolian pine, forests and plantations should be conducted in the future.

Keywords: *Pinus sylvestris* var. *mongolica*; Mongolian pine; Sandy land; Natural regeneration; Canopy openness; Forest gap; Regeneration index

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Introduction

The total area of desertification in sandy soil has reached 1.53×10^9 hm^2 in China (Jiang and Zhu 1993; Zhu *et al.* 2003a). Most of the sandy soil distributes in "Three North" regions (Northwest, North and Northeast of China) (Jiang and Zhu 1993), which are characterized by low and unreliable precipitation, extremes temperature, strong wind, high evaporation demands, and poor soils. Planting trees as a main countermeasure to construct protection system against sand movement or sand storm and to improve environmental quality has had a long tradition in the worldwide (Jiao 1989). In China, the "Three North" Protective Forest System Project (TNPFSP), which covers more than 42.2% of area of China, including 13 provinces or autonomous regions, was started in 1978. The total area of the protective forests has attained to 2.35×10^7 hm^2 till the end of 2003 (From Xinhua News, Oct. 09, 2004, http://www.chinagateway.com.cn/chinese/huanjing/32257.htm) in the four planned periods (There are total three stages including 8 periods in the TNPFSP from 1978 to 2050. The first period: from 1978 to 1986, the second period: from 1987 to 1996, the third period: from 1997 to 2000, and the fourth period: 2001-2010). The project has increased the forest coverage of "Three North" from 5.50% to 7.34% in the past twenty six years. More than 3.30×10^7 hm^2 farmland, sandy land and pasture have been protected by the protective forest system (From Xinhua News, Oct. 09, 2004, http://www.chinagateway.com.cn/chinese/huanjing/32257.htm).

Mongolian pine (*Pinus sylvestris* var. *mongolica*), a geographical variety species of Scotch pine (*P. sylvestris*) (Jiao 1989; Kang *et al.* 2004), is one of the most important tree species in TNPFSP. It naturally distributes in Daxing'an Mountain and Hulunbeier sandy plain of China, and parts of Russian and Mongol (N46°30'–53°59', E118°00'–130°08'). The vertical distribution range is from 600 m to 2 000 m above sea level (ASL) (Wang *et al.* 1996; Zhu *et al.* 2003a). The natural distribution of Mongolian pine on sandy land includes Honghuaerji, Haila'er, Wangong, Cuogang, He'erhongde, Hunhe, and Ha'erhahe areas in Inner Mongolian Autonomous Region, China. Of which, the largest area of the natural forest, which is about 200 km long and 14 km to 20 km wide at its mean on sandy land, is Honghuaerji (N47°35′–48°36′ E118°58′–120°32′) (Fig. 1).

After the success of the tree species introduction from Honghua'erji to southern ke'erqin sandy land in the 1950s, Mongolian pine plantations have been developed in a large scale of sandy land in "Three North" of China because of its characteristics such as cold-resistance (-40℃ to -50 ℃), drought resistance, and broad adaptation (Zeng *et al.* 1996). Currently, the area of Mongolian pine plantations on sandy land reached more than 3.00×10^5 hm^2 in "Three North" regions of China. Although establishing Mongolian pine plantations on sandy land had been successful, decline phenomena such as top withered, lower growth and dead stems often occurred in the earliest plantations since the beginning of 1990s, especially, the regeneration in plantations on sandy land has hardly happened. However, the natural forests on sandy land (i.e., in Honghuaerji) have showed a very healthy situation at the same growth stage of the planta-

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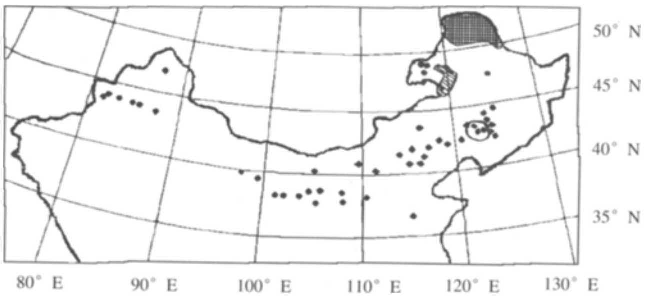
tions, i.e., the natural regeneration can carry out normally (Zeng *et al.* 2002a). In order to explore the regeneration problems in *P.* Mongolian pine plantations on sandy land, it is important and significant to understand why the natural stand on sandy land can regenerate, and how the regeneration occurs, firstly. In addition, regeneration of the responses of the species to stand structure or gap situation has a significant implication for general model of forest dynamics (Canham 1989; Nakagawa *et al.* 2003; Gagnon *et al.* 2004).



Natural Mongolian pine forests in mountainous area
Natural Mongolian pine forests on sandy land (Honghuaerji)
Planted Mongolian pine forest on southern (Keerqin sandy land)
Planted Mongolian pine forest on sandy land of "Three North" regions

Fig. 1 Distribution of *P. sylvestris* var. *mongolica* forests in China

Site description

The investigation was conducted at the natural Mongolian pine forests on sandy land at Honghua'erji, Hulunbei'er sandy plain of Inner Mongolian Autonomous Region (NHHI), China (Fig. 1). The natural Mongolian pine forests on sandy land in NHHI became the National Nature Reserve Area (NNRA) in 1998, with a total area of 20 085 hm^2. The forest coverage is 83.5%. The general topography of the NNRA is flat sandy land. There are two major soil types, i.e., sandy soil and meadow sandy soil. The contents of available phosphate and available nitrogen were 0.02%–0.03% and 0.010%–0.015%, respectively (Zhu *et al.* 2003a).

The climatic conditions of the area belong to the high latitude, low altitude, chilly, and semi-humid forest-pasture area. The elevation ranges from 767 m to 1 155 m. The relative height difference is 388 m. The annual precipitation ranges between 260 mm and 490 mm (long-term mean value: 378 mm), evaporation ranges between 1 000-1 460 mm (mean value: 1 174 mm). Annual mean temperature is -3.7 ℃. The annual sunlight is 2 800 hours, and the frostless period is around 90 days (Zhu *et al.* 2003a).

The vegetation of herbaceous species in the NNRA belongs to Davuri-Mongonlian flora. The species prevailing in NNRA include *Filifolium sibricum, Stipa baicalensis, Festuca ovina, Hemerocallis keiskei, Sanguisorba officinalis, Saposhnikovia davuricuta, Iris dichotoma, Pulsatilla turczaninovii, Bupleurum* sp., *Polygomatum humile, Potentilla fragarioides, Carex* spp.

Methods

The research on the regeneration of natural Mongolian pine forests on sandy land in NHHI (N47°35′-48°36′ E118°58′-120°32′) was conducted from July to August of 2004. In NNRA, twenty sample plots were set up on the stands with different stem densities and ages. The sample plots were squares of 20 m × 20 m (higher stem density) or 40 m × 40 m (lower stem density) according to stem densities. In addition, regeneration in forest gaps was also investigated. Global Positioning System (GPS) (eTrex Vista, USA) was used to locate the sample plots.

Stand characteristics

The following investigations of stand were conducted for each sample plot. 1) Stand density: individual stems in the sample plot were counted completely for determining the current stand density. 2) Stand age: at least 5 standard trees were selected for estimating the average age for natural forest using increment borer (the age below the increment borer was estimated according to the regenerated sapling at the same height). 3) Average height of stand: 10 heights of individual stems, whose diameters were around the average diameter, were measured for estimating the average tree height; suppressed trees were not included in the height estimation (Dyer and Bailey 1987; Zhu *et al.* 2003a). 4) Diameter at breast height (DBH): diameter at height of 1.3 m of all individual stems in the sample plot was measured, and stems whose DBH more than 4 cm were recorded. 5) Vegetation: species, coverage degree were investigated.

Canopy openness

Canopy openness (CO) was estimated using hemispherical photographs (Zhu *et al.* 2003b; Hardya *et al.* 2004), which were taken using a digital hemispherical camera (Nikon, Coolpix 910, Japan, f=7-21 mm) with 180° fish-eye converter (Nikon, FC-E8, f=8-24 mm). The hemispherical images were taken in the center of each sub-square, in which seedlings were investigated (Fig. 2). The camera was mounted on a tripod, leveled horizontally using a bubble level, and oriented such that north corresponded to the top of the photograph. The images were taken on the overcast day to avoid the influence of cloud and processed by software of LIA for Win32 (http://hp.vector.co.jp/authors/VA008416/), which was developed by Yamamoto (2000) to process and analyze the digital hemispheric images. The software can divide the hemispherical image into 89 doughnuts by zenith angle. Therefore, canopy structure data indices (Sky factor, canopy openness, effective LAI) can be extracted by the image area eliminating the outer doughnuts that the canopy openness of the doughnuts less than 0.01 (Fig. 2) (Zhu *et al.* 2004, 2005). The mean canopy openness of the sample plot was calculated by averaging all images taken in the sample plot.

Census of seedling regeneration in sample plots

10 to 14 of 1 m × 1 m squares (according to the area size of the sample plot) were taken for counting the number, age, and height of seedlings in each sample plot (Fig. 2). In each square, the seedlings were classified into four classes according to their ages, i.e., less than 2 years, more than 3 years and less than 5 years, more than 5 years and less than 10 years, and more than 10 years. The regeneration index suggested by Tsitsoni (1997) was applied, i.e., the number of seedlings per square meter, in this investigation. For each sample plot, the mean regeneration index was calculated.

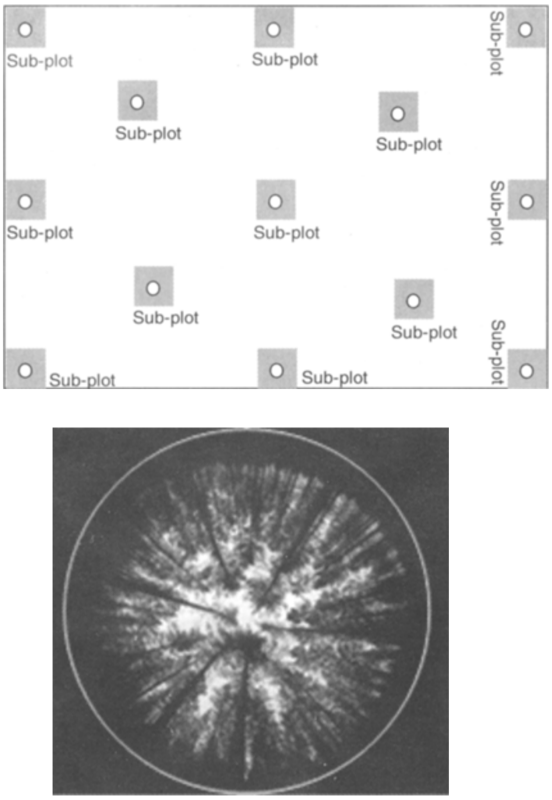


Fig. 2 Scheme for making seedling census (sub-plots, 1 m×1 m square), and canopy openness measurement (○)

Census of seedling regeneration in forest gaps

Census of seedling regeneration in forest gaps was conducted in three types of gaps, i.e., the circle-gap (Fig. 3A), narrow-square gap (Fig. 3B) and wide-square gap (Fig. 3C). Stripes of 1-m width through the gap center in east-west and south-north transects were designed for the census in the circle gaps. Gap positions were delineated by dividing at drop line in the east-west and south-north transects into sub-plots in interval of 1 m from the gap center (O) in actinoid directions (O→W, O→E, O→S, and O→N; O, the center of the gap) for the circle-gap (Fig. 3A) (Zhu *et al.* 2003c). Only east-west or south-north transects from one edge to the other were designed for the census of the narrow-square gaps and wide-square gaps (Fig. 3B, 3C).

All seedlings and the corresponding ages distinguished by seedling verticils (whorls) presented in each sub-plot were recorded. The height of each seedling was determined by measuring the distance from the forest floor (soil surface) to the shoot tip, or the top part of the seedling.

Data analysis

The relationships between the regeneration index and CO (stand structure), stem density, area density, and stand age were tested by analysis of variance (ANOVA). The stand characteristics of sample plot data are summarized in Table 1.

Results

Regeneration in the sample plots

The variation of regeneration indexes in each sample plot was presented in Table 2. The ages for most of the regenerated seedlings were less than 10 years (Table 2), and the regeneration index was considerably different in various plots. The largest one was from No. 8 sample plot, reaching 29 seedlings $\cdot$ m^{-2}. The least ones were appeared in sample plots of No. 4 and No. 5, counting to nearly 0 seedlings $\cdot$ m^{-2}. The regeneration index in each sample plot was influenced by stand density, area density, mean age, mean canopy openness or leaf area index (LAI) (Dai 1996; Myers *et al.* 2000; Vickers and Palmer 2000; Page *et al.* 2001). The relationships between regeneration index (total regeneration index) and the stand structure factors (Equation 1) were tested. The statistical analysis indicated that significant relationships were found between the regeneration indexes and mean stand age and stem density (Table 3).

$$RI = ax + b \tag{1}$$

where RI is the regeneration index (seedlings $\cdot$ m^{-2}), x represents the factors of stem density, area density, mean age, mean canopy openness or leaf area index (LAI), a and b are the coefficients.

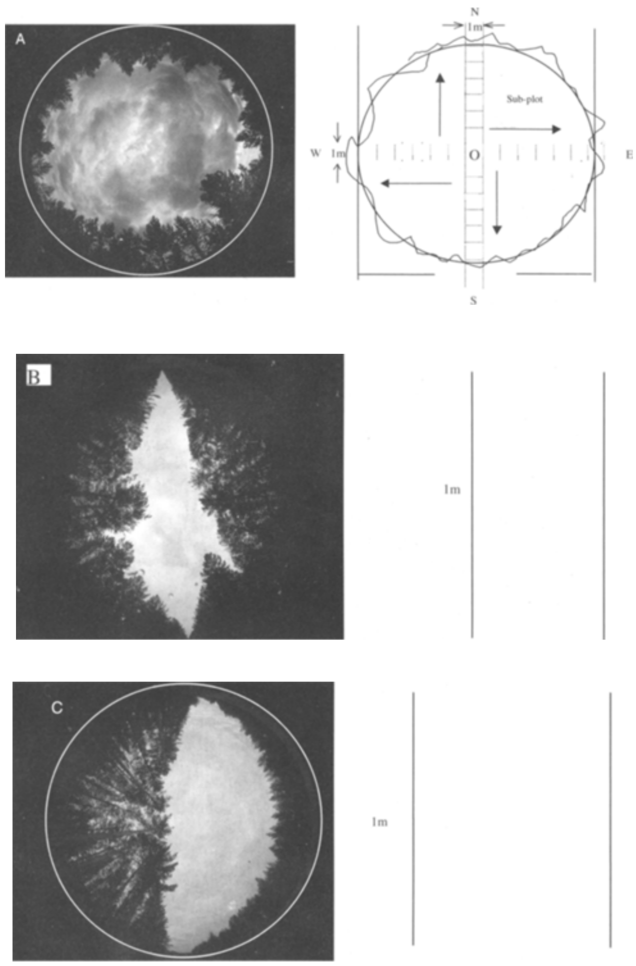


Fig. 3 Scheme for seedling census in different gaps

A: circle-gap, B: narrow-square gap (10 m in width), C: wide-square gap (about 30 m in width)

It can be seen from Table 3, the most significant factor contributing to regeneration index was the mean age of the stand although the mean age is not the direct factors influencing the natural regeneration. The regression relationships between the regeneration indexes in relation to the factors of mean stand age,

stem density and area density were confirmed by the statistical treatment (Table 4).

Table 1. Mean stand characteristics of sample plots

Sample plot number	Plot area (m^2)	Stand density ($stem \cdot hm^{-2}$)	Mean age	Minimum DBH (cm)	Maximum DBH (cm)	Mean DBH (cm)	Basal area ($m^2 hm^{-2}$)	Stand height (m)	Mean canopy openness	Altitude (m)
No.1	900	1489	46.0	6.8	67.0	18.0	44.23	14.5	*0.281 (0.017)	956.5
No.2	1250	536	65.0	1.4	44.0	19.9	27.15	15.6	0.306(0.032)	873.5
No.3	900	378	81.0	11.0	35.0	25.0	19.27	14.2	0.407 (0.077)	861.3
No.4	400	5675	32.0	2.1	67.0	8.1	44.86	10.5	0.241 (0.012)	835.3
**No.5	800	525	25.0	4.8	17.1	12.1	6.48	5.3	0.578 (0.067)	841.5
No.6	400	3550	43.0	4.1	28.1	11.8	45.84	11.4	0.223 (0.012)	841.8
No.7	1200	550	75.0	4.3	44.5	25.4	31.75	14.4	0.255 (0.023)	913.3
No.8	1600	238	86.0	21.1	45.8	35.0	23.57	18.2	0.259 (0.031)	925.5
No.9	900	1367	51.0	19.6	31.0	9.5	43.54	14.3	0.405 (0.022)	828.0
No.10	1200	325	58.0	16.5	30.0	23.5	14.49	16.2	0.422 (0.025)	829.5
No.11	1200	1092	48.0	2.5	36.2	18.4	33.19	14.0	0.248 (0.024)	836.3
No.12	900	1000	51.0	8.4	36.8	19.6	31.92	14.2	0.287 (0.016)	849.8
No.13	900	456	55.0	20.0	41.7	30.2	33.74	18.5	0.276 (0.022)	828.3
No.15	900	633	49.0	14.4	36.9	24.5	31.06	15.1	0.276 (0.028)	847.8
**No.17	900	989	32.0	10.0	25.5	18.4	27.14	10.3	0.260 (0.016)	816.3
**No.18	900	1322	31.0	6.3	23.5	15.6	26.70	8.6	0.271 (0.043)	813.5
**No.19	900	1156	48.0	10.7	29.3	19.4	35.44	11.8	0.267 (0.015)	775.0
**No.20	900	522	49.0	12.0	29.1	20.7	18.45	12.0	0.315 (0.032)	764.3

* Data in the bracket were standard errors.

** Plantations at Honghuaerji

Table 2. The regeneration indices for all age classes and all sample plots of *P. sylvestris* var. *mongolica* forest on sandy land

Sample plot numbers	Regeneration index (seedlings · m^{-2})				
	≤2 years old	3-5 years old	5-10 years old	≥10 years old	Total
No.1	1.63	0.38	0	0	2.00
No.2	4.9	4.1	0.9	1.7	11.30
No.3	0.4	4.6	14.5	0	19.43
No.4	0.1	0.0	0.0	0.0	0.08
No.5	0.1	0.0	0.0	0.0	0.08
No.6	1.6	0.4	0.0	0.0	2.00
No.7	3.4	9.4	7.1	0.0	19.85
No.8	3.0	23.7	2.3	0.0	29.00
No.9	0.2	2.2	1.5	0.3	4.31
No.10	0.2	4.8	2.1	0.1	7.11
No.11	0.3	4.3	2.3	0.0	6.83
No.12	0.0	4.2	7.3	0.1	11.58
No.13	1.0	4.5	1.4	0.2	7.10
No.15	0.8	1.6	4.8	0.0	7.20

Table 3. Analysis of variance of the relationship between regeneration index and the structure factors of stem density, area density, mean age, and canopy openness

Structure factors	d.f.	Related coefficient	Mean square	*F*	*p*
Stem density	11	0.615	48.090	6.098	0.033
Area density	11	0.603	49.306	5.701	0.038
Mean age	11	0.942	8.720	78.775	0.000
Canopy openness	11	0.046	77.252	0.021	0.887

Table 4. Regression statistics for determination of coefficients in Equations (2-4), which expressed the relationship between regeneration indexes and stand factors

	RI- A_m	RI- D_s	RI- D_a
Statistics for testing the significance of the regression equations			
R^2	0.8819	0.5555	0.3814
Standard error	0.8701	0.5111	0.3195
F-value	74.6799	12.4982	6.1652
Significance F	0.0000	0.0054	0.0324
Statistics of regression equation based on *t*-test			
Coefficient a in equation (1)	0.5016	-6.7039	-0.5404
Standard error	0.0580	1.8963	0.2177
t-value	8.6418	-3.5353	-2.4830
Significance *p*	0.0000	0.0054	0.0324
Coefficient b in equation (1)	-18.6724	55.1942	27.4677
Standard error	3.4735	12.8065	7.1960
t-value	-5.3757	4.3099	3.8171
Significance *p*	0.0003	0.0015	0.0034

The results of regression analysis (Equations 2-4) showed that the regeneration index increased with increase of mean stand age, and decreased with the increase of stand density or area density.

$$RI = 0.5016A_m - 18.6724 \tag{2}$$

$$RI = -6.7039\ln(D_s) + 55.1942 \tag{3}$$

$$RI = -0.5404D_a + 27.4677 \tag{4}$$

where A_m is the mean age of the stand (year), ranged between 30

years and 90 years; D_s the stem density (seedlings·hm^{-2}), ranged between 230 seedlings·hm^{-2} and 5 670 seedlings·hm^{-2}; D_a the area density (m^2·hm^{-2}), ranged between 14 m^2·hm^{-2} and 45 m^2·hm^{-2}.

Regeneration in the forest gaps

The general exposure of the circle-gap is the gap center. The characteristics of natural regeneration in two-size circle gaps of the Mongolian pine forest on sandy land are presented in Fig. 4. The regeneration index was considerably influenced by the within-position in the gap. There was lower regeneration index in the center of the circle-gaps, but higher regeneration index occurred at east edge (Fig. 4A) and south edge (Fig. 4B) of the circle-gaps. The seedling or sapling age ranged from 1 year to 38 years (mean age was 7 years).

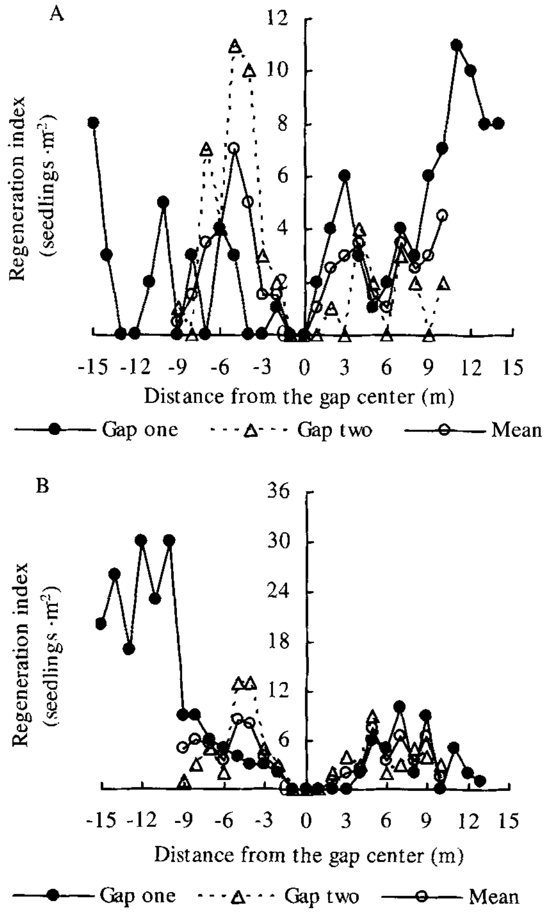


Fig. 4 Distribution of regeneration index at circle gaps (0 represents the center of the gap,)

(A) west–east transect, plus: from the gap center to east edge of the gap, minus: from the gap center to west edge of the gap, and (B) North–south transect, plus: from the gap center to north edge of the gap, minus: from the gap center to south edge of the gap

In the narrow-square gaps (width=10 m), the regeneration index increased from the north edge to the south edge (Fig. 5). The mean value of the regeneration index in the 5 narrow-square gaps was 0.2 at the north edge, at the middle about 5.0, and at the south edge more than 10.0. The regenerated seedlings were younger than 13 years old (between 1 year and 13 years).

In the wide-square gaps (width=28–29 m), the regeneration index showed the similar tendency to that of circle-gap, i.e., the regeneration index peaked at the east and west edges of the gaps, but not peaked at the center of the gaps (Fig. 6). The mean value of the regeneration index in the 3 wide-square gaps was 7.0 at both east and north edges, but at the middle about 2.0. The regenerated seedlings were younger than 10 years old (between 4 years and 10 years).

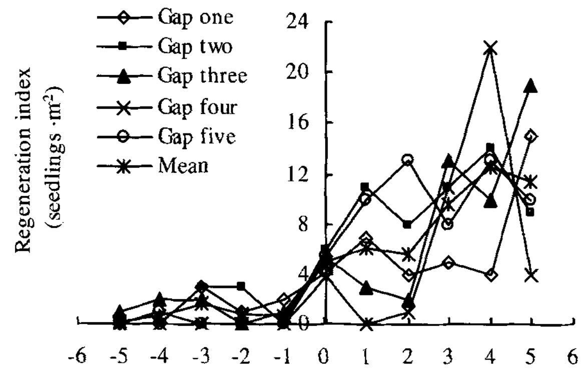


Fig. 5 Distribution of regeneration index at the narrow-square (about 10 m) gaps (minus represents north, plus represents south)

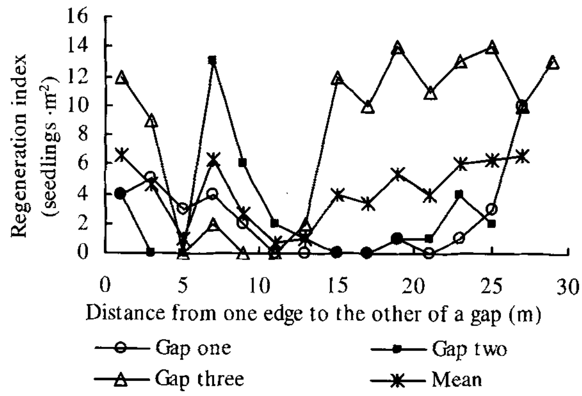


Fig. 6 Distribution of regeneration index at the wide-square (about 29 m) gaps (from the east edge to west edge)

Discussion and conclusions

The analysis of the regeneration results indicated that the natural regeneration of Mongolian pine in the study area was satisfactory in the mature forest stands and the gaps. A fact that can be attributed to the adaptation mechanisms evolved by the tree species is illustrated, i.e., Mongolian pine has been called "easily-regenerated" (Shen *et al.* 1992; Zeng *et al.* 2002b; Zhu *et al.* 2003a; Kang *et al.* 2004). From a silvicultural-biological point of view, Mongolian pine is a photophilic, drought resistant species, particularly the one from the origin of Hulunbei'er sandy land prefers sandy soil (Jiao 1989). However, according to the results observed in this investigation (Table 3), the regeneration index seemed not to be influenced by the canopy openness although Mongolian pine is a photophilic species. We try to explain the reason why the phoyophilic tree species is not in relation to the canopy openness closely, i.e., on the one hand, the

seedlings in the sample plots (without gaps) may not grow into the upper layer of the canopy without canopy gap or large disturbance, e.g., fire, wind/snow damage or clear cutting etc. (Bailey and Covington 2002); on the other hand, the Mongolian pine seedlings might endure some shading understory before they enter into the dominant layer of the stand, at least before sapling formation, e.g., before 15 years.

Additionally, the age of most regeneration seedlings in the sample stands was less than 10 years, this may be explained by the fact that the fire disturbance occurred 10 years ago (1994) in Honghua'erji, in which the older seedlings (more than 10 years old) were killed (Kaufmann *et al.* 2003). If the fire really influenced the seedlings in the sample plots, then the Mongolian pine seedlings should have shade-tolerant ability before a certain age, or the seedlings can be survival under the canopy.

As presented in the results, the analysis of variance showed that the stand age was an important factor determining the natural regeneration indexes in the sample stands; the lowest values occurred at the youngest stands as shown in Table 2 (sample plots of No. 1, 4 and 6). Concerning the total mean regeneration indexes in the sample stands (varied between 0.10 and 29.0), it can be seen that when the accumulated percentage of stems whose age less than 50 years got to 50, the regeneration indexes were very low (0.1-4.3), but in the older stand (about 80 years, sample plots of No. 3, 7, 8), the regeneration indexes reached about 20 (Table 2, refer to Fig. 7 for the age distribution). This means that the regeneration of Mongolian pine depends on tree age. Even the lowest regeneration index of 0.1, the seedling bank (1 000 seedlings · hm^{-2}) should be enough for regenerating if the other factors satisfy the conditions of regeneration.

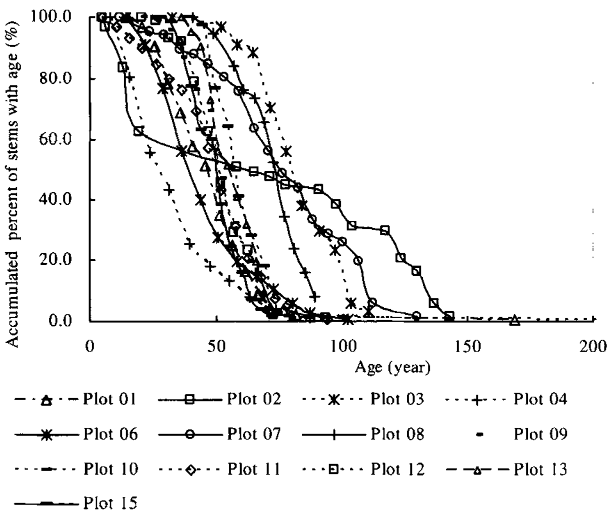


Fig. 7 Distribution of age classes of the stems in the sample plots (Refer to Table 2 for the regeneration patterns)

As resulted from the statistical analysis (Table 4), the stem density or area density is another important factor which may influences the natural regeneration. Among the sample stands, the regeneration indexes in stem density more than 1 000 seedlings · hm^{-2} were very low (Table 1, Table 2). This result suggests that denser stand influences the regeneration of Mongolian pine.

The mean values of regeneration indexes ranged from 2.4 to 8.1 in the gaps. These values of regeneration indexes in forest gaps were satisfactory in comparison with those observed in the younger stands, e.g., the stands below 50 years. The largest age of regenerated saplings in the large gap reached 38 years, but most regenerated saplings were less than 10 years (Fig. 8 A, B, C).

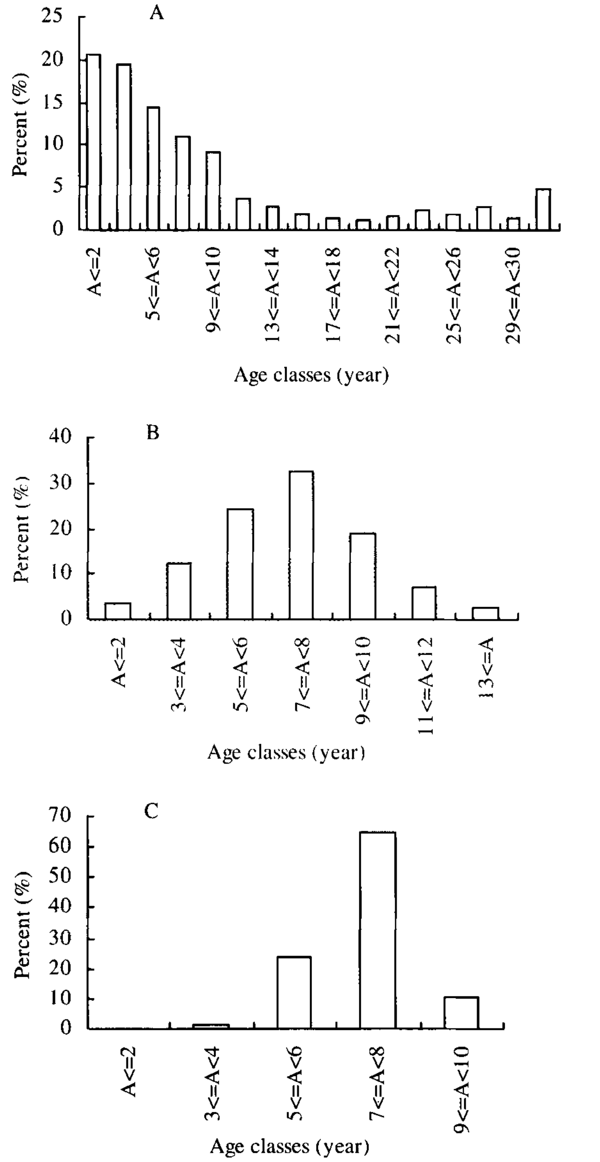


Fig. 8 Distribution of seedlings according to age classes in the gaps
A: Circle gap, B: narrow-square gap, C: wide-square gap

Generally, natural regeneration in gaps should be influenced by the time of gap formation, but the gap age was not investigated in this study. The results also showed that the regeneration of Mongolian pine forests was influenced by the gap size in the circle gaps; both sapling age and regeneration index increased with an increase in gap size. The above mentioned result was similar to Lertzman *et al.* (1996), Wang *et al.* (1998) and Zhu *et al.* (2003c). The distribution patterns of seedlings in gaps did not support the gap-partitioning hypothesis (Wang *et al.* 1998), i.e., the seedlings of light-demand tree species in northern hemisphere distribute in the north edge of the gaps, as seen in the results, Mongolian pine seedlings distributed in the south and east edges of the gaps.

Based on the above analysis, it is clear that a satisfactory

natural regeneration was occurring in the older Mongolian pine stands (more than 50 years) and gaps in Honghuaerji, which is the origin of sandy land Mongolian pine forests. The characteristics of the natural regeneration can be summarized as follows: The natural regeneration of Mongolian pine was in relation to stand age closely, and then to the stem density, natural regeneration of Mongolian pine nearly did not occur before 50 years; Mongolian pine seedlings had some shade-tolerant ability under the canopy; natural regeneration of Mongolian pine demanded gaps or disturbances such as forest fire, wind/snow damage or clear cutting etc.

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